Ocean Regulation of Climate by Heat and Carbon Sequestration and Transports (ORCHESTRA)

1. Executive Summary

Programme Objective: Advance our understanding of, and capability to predict, the Southern Ocean's impact on climate change via its uptake and storage of heat and carbon.

ORCHESTRA will significantly reduce current uncertainties concerning how the uptake and storage of heat and carbon by the ocean influences global climate, by conducting a series of unique fieldwork campaigns and innovative model developments. This is a leading-order challenge of great societal relevance and strategic importance to NERC (*1*), but progress is currently hampered by poor provision of data with which to improve understanding of the key processes and constrain their rates, and inadequate representation of the key dynamics in ocean and climate forecast models. The area requiring the most urgent improvement is the Southern Ocean, where many of the controlling mechanisms and exchanges occur, and yet where data coverage is most sparse, dynamical understanding is weakest, and climate models show greatest biases and least realistic depictions of processes. ORCHESTRA will address these issues using the UK's world-leading capability and infrastructure in ocean and high-latitude research, including major ship expeditions, autonomous vehicle deployments and research aircraft campaigns, with the data collected used to improve model schemes and validate model outputs, and with the improved capability fed through to UK climate model development. ORCHESTRA represents the first fully-unified activity by NERC institutes to address these challenges, and will draw in national and international partners to provide community coherence, and to build a legacy in knowledge and capability that will transcend the timescale of the programme itself.

2. Motivation and Background: Climate change is one of the most urgent issues facing humanity and life on Earth. A critical gap in our understanding of the climate system concerns the uptake of heat and carbon by the oceans. Over 93% of the extra heat now present in the Earth System because of global warming is in the ocean (*2*), with the recent Intergovernmental Panel on Climate Change (IPCC) assessment showing strong increases in the energy stored in both the upper (~170 x 10^{21} J) and deep ocean (~80 x 10^{21} J) since the 1970s (*3*). The global ocean is also the largest reservoir of carbon in the climate system, and contained approximately 60 times more carbon than the atmosphere in the pre-anthropogenic era (*4*). Since the industrial revolution, the ocean has absorbed ~30% of anthropogenic CO_2 emissions (*5*), hence moderating the rate of climate change in the atmosphere.

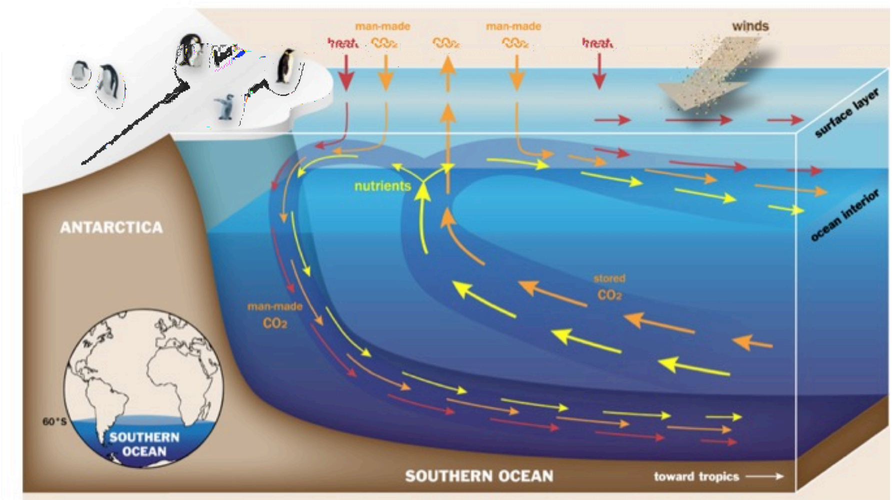

Figure 1. Schematic of the Southern Ocean overturning circulation. Deep waters upwell to the surface, and exchange heat and carbon with the atmosphere. They are transformed into new water masses that sink into the ocean interior, in the form of mode and intermediate waters (upper limb) and dense bottom water (lower limb), thereby removing heat and anthropogenic carbon from the atmosphere (image Tara Thean).

The Southern Ocean is disproportionately important in this context, accounting for ~50% of oceanic uptake of carbon, and >75% of the heat uptake (*6, 7*). This central climatic role is a consequence of its unique pattern of circulation. Strong winds and buoyancy forcing drive the world's largest current system (the Antarctic

Circumpolar Current; ACC), which flows continuously eastward around the continent, transporting large amounts of heat, carbon and other important tracers. Simultaneously, the pattern of surface forcing drives a divergent surface flow, drawing up water from ~2-3 km below (Figure 1), with up to 80% of global deep waters resurfacing in the Southern Ocean (*8*). These waters are then modified via strong atmosphere-ocean-ice interactions, with one product being the dense Antarctic Bottom Water (AABW) that forms in the subpolar gyres and spreads out to fill much of the global abyss (lower limb; Figure 1). The changing heat content and formation rates of AABW have implications for the planetary heat budget, sea level rise and the strength of the Atlantic meridional overturning circulation (AMOC) (*9, 10*). Also important are the lighter mode and intermediate waters that sink north of the ACC (upper limb; Figure 1), and which are known to be especially important climatically because of the large amounts of anthropogenic carbon they sequester from the atmosphere. The strength of this overturning circulation and the properties of the waters it transports are thought to be significantly variable on a range of timescales, with consequences for the present and future efficacy of the Southern Ocean sink for atmospheric carbon (*11, 12*).

The climatic impact of these processes is governed by (1) the magnitude and temporal changes of the heat and carbon exchanges across the sea surface, (2) the rate at which they are drawn into the ocean interior across the base of the upper-ocean mixed layer, and (3) the rate at which they are exported from the Southern Ocean via the large-scale circulation.

Concerning **(1)**, current state-of-the-art climate models are very sensitive to the magnitude and distribution of air-sea-ice exchange in the Southern Ocean, emphasizing the need to accurately represent such processes in such simulations to obtain reliable projections (IPCC AR5). The current scarcity of atmospheric and oceanic observations means that reanalyses used to force ocean-only models and validate climate models are poorly constrained in the Southern Ocean (*13*); this is especially true for the winter months when the dearth of data is most acute. Further, parameterisations used to estimate surface fluxes are uncertain and have not been tested in the full range of conditions typical of the Southern Ocean, including strong buoyancy forcing and extreme wind speeds and wave heights (*14*). Advancing our ability to simulate and predict air-sea-ice interaction in the Southern Ocean requires an increase in the collection of targetted observations, and also an assessment of the impact of observations on parameterisations, reanalyses, and models. The first question that ORCHESTRA will address is: ***Q1. What controls the exchange of heat and carbon across the air-sea-ice interface, and how well are these exchanges constrained by observations and reproduced by models?***

Concerning **(2)**, it is known that the physical and biogeochemical properties of the upper-ocean mixed layer are key factors in controlling exchanges of heat and carbon. Spatial and temporal changes in these properties are driven strongly by transfers across the base of the mixed layer, where tracers enter the ocean interior in new water masses, and where old waters are returned back to the surface layers. These transfers are controlled by a combination of processes including changes in mixed layer depth, time-varying wind forcing, and fluxes associated with mesoscale eddies. These processes occur on comparatively small scales, and are critically under-observed and poorly quantified/understood in the Southern Ocean. A high priority is to quantify the relative importance of each of the key processes, and to develop budgets for the upwelling, modification and subduction of new water masses. These budgets are currently unconstrained on virtually all timescales; improving our understanding and predictive capability concerning the ocean's role in climate change requires them to be developed for timescales from seasonal to decadal and centennial. The second question that ORCHESTRA will address is: ***Q2. What are the leading-order processes that control the rate at which heat and carbon enter the Southern Ocean interior in its different layers, and how will these rates change in future?***

The importance of **(3)** is illustrated by the fact that column inventories of anthropogenic carbon in the Southern Ocean are significantly lower than those in the North Atlantic, despite it being the former where most of the excess heat and carbon is taken up from the atmosphere (*5*). This is evidence that much of the heat and carbon that enters the Southern Ocean is exported to the rest of the globe by large-scale ocean circulation, thereby setting the levels and timescales of heat and carbon storage in each of the major ocean basins. It is known that the heat flux in the South Atlantic is equatorwards (not polewards like in other ocean basins), and that anthropogenic carbon is transported northwards here also, however there are major uncertainties concerning the level of variability in these transports, and also the dynamics of the large-scale circulation responsible for them. There is a need to better constrain these transports across a range of timescales, and to understand the key drivers that control their variability, so as to improve understanding and predictive skill concerning their effect on climate. The third question that ORCHESTRA will address is: ***Q3*** ***What are the size, variability and controls on basin-scale heat and carbon fluxes throughout the Atlantic sector of the Southern Ocean and outwards to the global ocean, and how will these change in the future****?*

3. Workplan: ORCHESTRA will address these three questions through a co-ordinated programme of targeted observations (Figure 2) and modelling across six NERC institutes (funded via LTSM) and the UK Met Office (no funding dependency). The research will be structured in three scientific workpackages described in this section. These will each use different combinations of scientific tools and infrastructure (e.g. T1 etc), full details of which are provided in Section 4.

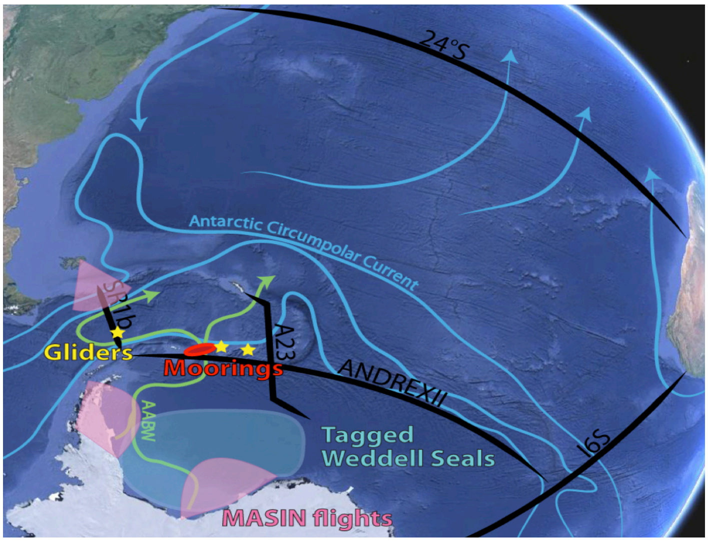

Figure 2. Schematic of ORCHESTRA fieldwork, including ship sections (black), mooring cluster (red), autonomous vehicle deployments (yellow), aircraft flights (pink), and seal tagging (green).

WP1: Interaction of the Southern Ocean with the atmosphere (NOC, BAS, PML, CPOM). To address Q1, WP1 will make and use new observations (T1, T4) of surface fluxes and their controlling parameters to better constrain the exchanges of heat and carbon across the surface of the Southern Ocean. This will be conducted across a range of conditions: the open ocean, partially ice-covered regions such as leads (cracks) and polynyas, and solid pack-ice. We will test new instruments for the measurement of air-sea-ice gas fluxes using laser absorption spectroscopy on RRS *James Clark Ross*, and assess their capability to provide accurate surface flux observations. Within this assessment, we plan to include a comparison with cavity ring-down spectrometer CO_2 flux measurements from aircraft flights in a range of surface conditions. An autonomous system integrating sensors, data logging and flux analysis processing will be developed for ORCHESTRA, and for future use on ships of opportunity. We will also develop a system to quality control historical surface flux and flux-related data from research vessels and analyse existing observations made in the unique conditions of the Southern Ocean.

ORCHESTRA will integrate the new and existing observations to critically assess current state-of-the-art fields of flux and flux-related parameters in atmospheric and oceanic reanalyses, used widely to force ocean models. We will assess new Earth Observation (EO) measurements and products (T5) that may more accurately represent the surface parameters that control air-sea exchange. Measurement, sampling and structural uncertainties in flux parametersations will be determined from direct flux measurements, including those made directly by ORCHESTRA. We will test whether any existing parameterisations are suitable for calculating air-sea exchange under the extreme Southern Ocean conditions: if not, improved parameterisations will be proposed.

The sensitivity of heat and carbon fluxes in ocean-only models to realistic uncertainty in both forcing fields and flux parameterisations will be assessed via an adjoint modelling approach (T9). Perturbation experiments will quantify the impact of uncertainty in surface forcing on the model estimates of the ocean state and key processes (T8). The air-sea-ice fluxes of heat, momentum and CO_2 in the climate and Earth System simulations (T7) will be assessed at both high and low resolution using observations and uncertainty estimates from ORCHESTRA. These assessments will be used to understand flux-related biases in the UK Earth System Model, important in reducing the unrealistically warm Southern Ocean near-surface temperatures seen in this and other models.

WP2: Exchange between the upper-ocean mixed layer and the interior (BAS, NOC, SMRU). To address Q2, WP2 will combine observationally-derived data and model simulations to determine and understand the exchanges between the ocean mixed layer and its interior in unprecedented detail. We will use ocean profile data (T2, T3) to produce 10-day maps of temperature and salinity at 1° resolution for the period since 2004. These will be analysed alongside improved estimates of surface fluxes (see WP1) and EO data (T5) to derive the first seasonally-resolved, decade-long subduction budgets for mode and intermediate waters in the Southern Ocean. Carbon subduction will be estimated by combining these with publicly-available carbon measurement compilations, and with ship section observations (T1). We will investigate the role of atmospheric forcing (including large-scale modes of climate variability, e.g. the Southern Annular Mode, SAM, and the El Niño/Southern Oscillation phenomenon, ENSO) in influencing heat and carbon subduction on both seasonal and interannual timescales, and the role of individual mixed layer/subduction processes in setting the net budget. Multi-month glider missions (T3) will provide detailed information on key processes, with autonomous measurements charting the erosion of water masses created in winter, and allowing us to determine the effect of individual weather events on the flux of heat into the ocean interior.

The processes underpinning the observed relationships, as well as larger-scale and long-term trends, will be investigated in model-based analyses (T7 & T8) using the same budget approaches applied to the observations. Subduction-related metrics will permit quantitative comparisons across diverse model ensembles including climate/Earth System models (T7) and forced-ocean simulations (T8). Perturbation experiments aimed at understanding and quantifying the dynamical relationship between mixed layer processes and seasonal/interannual subduction will be conducted (e.g. shortwave/turbulent heat flux perturbation, modified mixing schemes etc.), with the perturbations being informed by adjoint model runs (T9) and the relationships derived in the observational and low-resolution model subduction analyses. These analyses will inform improved model representation of mixed layer processes (e.g. Langmuir turbulence) in setting subduction rates and sensitivities. The downslope injection of dense waters into the deep Weddell Sea (a key process in AABW formation, which present models simulate poorly) will be made more realistic using improved vertical coordinates to reduce spurious mixing, and by including the effect of tides. Intercomparisons of coupled runs with ocean-only climate scale models (T7) and high-resolution models (T8) will be conducted to examine and improve existing biases and to enable quantification of structural uncertainty, the impact of mesoscale eddies, and the role of coupled feedbacks in setting subduction and overturning circulation.

WP3: Exchange between the Southern Ocean and the global ocean (NOC, BAS, PML, BGS, Met Office). To address Q3, WP3 will conduct budget analyses using the hydrographic/tracer sections (T1) to diagnose the three-dimensional velocity field of the waters entering, leaving and recirculating within the South Atlantic sector of the Southern Ocean. This method generates optimally-constrained velocity fields by invoking conservation of properties in specific layers. It will be informed by directly-measured velocities on the cruises, and the rate of mixing between layers constrained using turbulent mixing estimates from vertical microstructure profilers. Combination with the measured tracer fields will enable transports of key properties (including heat and carbon) to be derived, for each of the different layers, and in totality. An overall budget will be constructed for a box enclosing the entire South Atlantic sector of the Southern Ocean, enabling us to diagnose its net role in the global heat and carbon cycles. The location of the ANDREXII section subdivides this box into a northern region enclosing the ACC and a southern region enclosing the Weddell Gyre. Our analyses will thus separately quantify the fluxes associated with the upper and lower limbs of the Southern Ocean overturning.

Each of the ORCHESTRA hydrographic/tracer sections has been occupied in the last 5-10 years with full suites of physical/biogeochemical measurements**.** Using these, we will diagnose the changes in the storage of heat and carbon occurring over a quasi-decadal interval, and interpret them in terms of known changes in climatic forcing and increasing atmospheric CO_2 concentrations. The temporal representativeness of the sections will be assessed using profiling float and glider data (T2, T3), mapped as per WP2 above. Additionally, we will use data from the profiling floats to produce sections at 10-day intervals and 0.25^o spacing along the hydrographic section lines, and thereby examine changes in upper ocean properties and transports on seasonal to decadal timescales. The impact of physical variability on the changing distributions of biogeochemical parameters (including anthropogenic carbon) will be quantified using statistical relationships between them and coincident temperature and salinity observations. Where available (e.g. from the international Southern Ocean Carbon and Climate Observations and Modelling (SOCCOM) programme; see Project Partner statement), oxygen will be used as an independent predictor. For the mixed layer, we will use the publicly-available Surface Ocean CO_2 Atlas and ORCHESTRA-generated observations to constrain short-term variability in surface disequilibrium.

We will determine the time-variability of transports and heat content associated with the lower limb of the Southern Ocean overturning using deep-ocean moorings data (T6) and annual repeats of short hydrographic sections (T1), the locations of which are optimally chosen to capture the core of the AABW as it flows north to become the bottom waters of the AMOC. We will test hypotheses that relate AABW export from the Weddell Gyre to changes in wind-forced and buoyancy-forced circulation by relating the observed variability in the transport to changes in surface circulation derived from satellite altimetry (T5). The dynamics behind such linkages will be explored fully using high-resolution ocean modelling (T8).

The size and variability of the modern (T7, T8) and projected (T7) Southern Ocean heat and carbon budget will be estimated in a range of ocean and coupled climate models. The sensitivity of the component parts of the budgets (uptake, storage, export) to model scenario, resolution and diversity will be assessed across timescales from seasonal to centennial, and impacts of ORCHESTRA-derived model improvements will be quantified.

4. Tools, fieldwork and data generation: Details of the specific tools and techniques to be used by the ORCHESTRA WPs are:-

T1. Ship-based campaigns *(NOC, BAS, PML, BGS).* The ORCHESTRA hydrographic/tracer sections will be conducted across Drake Passage (SR1b), the northern Weddell Sea/Scotia Sea (A23), the northern rim of the Weddell Gyre (ANDREXII) and across the South Atlantic (24S) (Figure 2). Section I6S will be performed by GO-SHIP Project Partners. Measurements will include temperature, salinity, dissolved oxygen, velocity, dissolved inorganic carbon, total alkalinity, inorganic nutrients, oxygen and carbon isotopes, and underway meteorological and surface ocean observations including pCO_2. These cruises have an additional requirement for transient tracer measurements, which will be pursued using other modes of funding. The SR1b and A23 sections will be repeated during each ORCHESTRA field season with hydrographic and underway measurements, in addition to single occupations with full tracers and carbonate system measurements. An autonomous shipborne system using eddy-covariance techniques will be developed to enable direct flux measurements including CO_2, heat and momentum (see also T4).

T2. Profiling floats and marine mammal tagging *(BAS, NOC, SMRU).* We will use publicly-available data from the network of Argo floats, and work with partners from SOCCOM to access such profiles that feature carbonate system measurements (see SOCCOM Project Partner statement). Argo profiles are extremely sparse in the Weddell Sea due to sea ice cover; we will address this by deploying oceanographic sensor packages on 30 Weddell seals across three field seasons. Unlike other species, Weddell seals remain in the pack-ice during winter, enabling data collection from high southern latitudes between February and October each year. Each package will provide 2-3 profiles of temperature and salinity per day, to be used alongside the Argo data.

T3. Autonomous vehicles *(BAS, NOC).* We will deploy autonomous underwater ocean gliders, which will conduct multi-month missions in key regions of the Southern Ocean. These will deliver data on ocean stratification, heat content, mixed layer depth and turbulent mixing over the upper 1 km, with previously-unobtainable temporal resolution. Deployment locations will include regions of known importance for transfers of heat between the Weddell Gyre and the ACC, and we will look to incorporate novel carbon sensors into these gliders as they become commercially available with the necessary quality and reliability. Further, we plan the first Southern Ocean deployment of an autonomous surface vehicle (ASV), proposed separately for funding by NOC, which will carry sensors for measuring air-sea flux-related parameters. If initial deployments proceed as planned, the ASV will be used to make important wintertime measurements in the Southern Ocean, including of near-surface ocean CO_2 concentration.

***T4. Aircraft flights** (BAS).* We will conduct field campaigns with the MASIN meteorological aircraft, flying out of Rothera and Halley research stations, and the Falkland Islands. These will deliver information on key variables relating to air-sea fluxes (surface and air temperature, wind, humidity, atmospheric CO_2, radiation, turbulent fluxes of heat, momentum and CO_2), including in different sea ice conditions and in different oceanic regimes (polynyas, upwelling regions, etc.). This fieldwork will be coordinated to coincide with *in situ* measurement campaigns where practicable, e.g. with seal tag measurements of upper ocean heat in the Weddell Sea (T2).

***T5. Earth Observation (EO) data** (CPOM, NOC, BAS, PML).* ORCHESTRA will use EO datasets to inform on the properties of the ocean, sea ice, and atmosphere, and on interactions between them. These datasets will include new satellite measurements that more accurately represent the surface parameters controlling air-sea exchanges, including SST from the ESA Climate Change Initiative, and wind speed measurements from Global Navigation Satellite System reflectometry to augment conventional satellite data sets in stormy conditions. With regard to ocean circulation, we will use AVISO satellite altimeter measurements of sea surface height (SSH) to derive surface geostrophic circulation. However, the spatial coverage of AVISO data is limited by sea ice. We will use specialised data processing developed by CPOM to extract useful estimates of SSH in the ice-infested regions. This relies primarily on using the shape of altimeter waveforms to detect leads in the ice pack, and also on the use of synthetic aperture radar data to track floe drift. These new measurements will enable us to extend the conventional estimates of surface circulation variability into the subpolar gyres with year-round coverage.

***T6. Deep-ocean moorings** (BAS).* ORCHESTRA will maintain a cluster of six deep-ocean moorings in Orkney Passage (South Scotia Ridge; Figure 2). This is the key gateway for the outflow of dense water from the Weddell Sea to lower latitudes, with around a quarter of all AABW transiting this gap. The moorings will collect year-round series of AABW temperature and transport. This work connects to the NERC-funded Dynamics of the Orkney Passage Outflow project, for which this array will be augmented with additional sensors in 2015-2017.

***T7. Climate/Earth System Modelling** (Met Office, NOC, BAS).* We will use the UK Earth System Model (UKESM) and its underlying physical climate model to conduct analyses of heat and carbon uptake and transport by the Southern Ocean, and their links to wider climate on decadal timescales. These will be run with 1º and ¼º-resolution oceans, with some runs at 1/12º available via linking to the EU-funded Primavera project. We will also use output from coupled and ocean-only model integrations submitted to the IPCC Coupled Model Intercomparison Projects (CMIP). CMIP5 is available now; CMIP6 will become available during the timeframe of ORCHESTRA. These resources will be used to elucidate key sensitivities in the uptake of heat and carbon, including scenarios, model diversity and resolution, using multi-model ensembles. Model improvements derived from ORCHESTRA will be pulled through to UKESM development.

***T8. Ocean-only modelling** (NOC, BAS).* We will construct an eddy-resolving (1/12º) sector model of the ocean south of 30ºS. This will be built using the NEMO model coupled to the Los Alamos sea ice (CICE) model, and will have 75 vertical levels. It will be run for a synoptic period (1979-present), overlapping the period of satellite and greatest *in situ* data availability. Model enhancements will include an improved ocean boundary layer using results from the NERC-funded OSMOSIS project, and inclusion of tides. Crucially, an improved vertical coordinate system will enable better depiction of the downslope cascading of dense water around Antarctica. A 60-year control run will be conducted, followed by ten 15-year perturbation experiments to examine the sensitivity of the model to changing surface forcings, mixing parameterisations and freshwater stratifications. A set of four 30-year perturbation runs will be conducted to investigate the response to changes in major modes of climate variability. Three 30-year runs will assess the improvements to AABW properties and transports.

***T9. Adjoint modelling** (BAS).* To determine how key forcings and model states affect the uptake and subduction of heat and carbon by the ocean, ORCHESTRA will conduct twenty 5-year runs of an adjoint model. These will isolate mixed layer and subduction sensitivity to surface forcing, and the adjoint-generated sensitivity maps will also be used to determine how to optimally perturb the high-resolution forward models (T8) to obtain the clearest response signals.

5. Milestones and Deliverables: Use of the above tools will enable the ORCHESTRA WPs to produce the following milestones and deliverables:-

1. A major observational program integrating ships, aircraft, satellites, mammals and profiling floats, enabling quantification of the transfers of heat and carbon across the sea surface, into the ocean interior and through the Atlantic sector of the Southern Ocean. (M: 2017-19).
2. Development and deployment of autonomous systems and innovative technology to progress our ability to measure year-round the fluxes and budgets of heat and carbon in the high-latitude oceans, including in ice-infested waters. (M: 2017-2019).
3. Developments to improve the skill of numerical models in simulating the Southern Ocean and its climatic influence, for inclusion in the IPCC process and policy development. (D: 2020).
4. Key quantifications of basin-scale budgets of heat and carbon in the Atlantic sector of the Southern Ocean, and their changes on timescales up to decadal (D: 2019).
5. The first decade-long, seasonally-resolved budgets for heat and carbon subduction in upper Southern Ocean water masses. (D: 2021).
6. Determination of the drivers and impacts of decadal-to-centennial changes in Southern Ocean subduction of heat and carbon (D: 2021).
7. Synthesis paper, landmark report and open science meeting showcasing ORCHESTRA science and legacy (D: 2021).

6. ORCHESTRA as LTS-M, and the ORCHESTRA team: The science questions that ORCHESTRA will address are of such a scale and complexity that no single institute worldwide has the capacity to address them. Required is an integrated team of scientists working across traditional institute/disciplinary boundaries in a coherent, strategic programme. The NERC-supported institutes in ORCHESTRA, working alongside national and international partners (see Project Partner statements and Wider Relevance), have the critical mass of scientific expertise across each of the relevant disciplines, with existing teams that can be readily deployed and committed to the programme for its duration. These institutes have considerable track records and past investments in the infrastructure, platforms and scientific expertise that ORCHESTRA requires, upon which we will build during the duration of the programme to enhance future scientific capability and the ability to deliver future ambitious programmes for the UK.

Each of the ORCHESTRA WPs will be an integrated effort across centres. They will draw together complementary expertise in marine meteorology (NOC) and ship-based observations of flux-related parameters (NOC, PML) with aircraft-based measurements (BAS) and EO (CPOM, NOC, BAS). Diverse water-column measurements are required for the transport analyses, made possible by expertise in hydrography (NOC, BAS), chemical analyses (BGS, NOC, PML), floats and mammal tagging (NOC, BAS, SMRU), autonomous vehicles (BAS, NOC), and moorings (BAS, NOC). Complementary expertise in ocean dynamics (BAS, NOC), adjoint modelling (BAS), regional (BAS, NOC) and global (NOC, BAS) ocean and climate models (Met Office, NOC, BAS) will be used to determine and understand the key processes concerning the ocean's role in climate change, and to deliver improved predictive skill.

7. Programme management: To manage the process of drawing these teams together to achieve the goals of ORCHESTRA, the programme will be organised as per Table 1, with an overarching coordination/synthesis WP4 running alongside the three science WPs. To ensure seamless connection between the WPs and full delivery of the programme, ORCHESTRA will have an internal management team, chaired by the PI and including the Centre Leads, plus the WP leads and key personnel with specific roles. Project support will be provided from the BAS Programme Office. The board will meet in person on a six-monthly basis to track progress and developments, decide upon responsive measures, and resolve minor issues; more frequent meetings will be conducted by videoconference. Major issues that this group cannot resolve will be transferred to the appropriate level, including Directors/Science Directors of the institutes. The *modus operandi* for the ORCHESTRA partners will be detailed in a Consortium Agreement, providing full clarity on issues including data sharing, authorship of articles, financial responsibilities, reporting responsibilities, and other matters important for the successful collaborative delivery of the programme. The criteria will be harmonious with NERC rules and guidelines for LTS-M and NERC-funded science in general. A Programme Advisory Group (PAG), membership to be agreed with NERC, will have oversight of ORCHESTRA.

		Yr1				Yr2				Yr3				Yr4				Yr5			
	Year	16	16	16	17	17	17	17	18	18	18	18	19	19	19	19	20	20	20	20	21
	Quarter	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1
WP1	Surface																				
Leader Kent	1.1: Observation and characterisation of surface fluxes	Ad C5								C6											
NOC, BAS, PML, CPOM	1.2: Dynamics and processes of exchange	Ad								C6		HR									
WP2	Subduction																				
Leader Meijers	2.1: Characterisation of subduction	HR C5								C6											
BAS, NOC, SMRU	2.2: Processes, dynamics and forcing of subduction					C5				Ad				HR C6							
WP3	Deep ocean																				
Leader McDonagh	3.1: Basin scale budgets, transports and inversion	HR C5								C6											
NOC, BAS, PML, BGS, Met Office	3.2: Deep variability, future trends and exports					C5				C6		HR									
WP4	Co-ordination																				
Leader Meredith	4.1: Project mngmt.																				
	4.2: Project board mtg.	●		●		●		●		●		●		●		●		●		●	●
All	4.3: External meetings	AB						AB		WS			AB					AB			IS
Observations	Ship Sections (**bold with Carbon**)			D1	S1			D2	S2 **24S**			**D3**	S3 **I6,A2**			D4	S4			D5	S5
	Ship Surface (F: Flux)				F				F				F	F		F	F	F		F	F
	Moorings (X: deploy)				X								X								X
	Aircraft (AC: flights)				AC1				AC2				AC3								
	Mammals (T: tagging)				T				T				T				T				
	Autonomous Vehicles																	A S V			
Milestones & Deliverables				1	1,2			2	1,2		2	1,2,4	1,2	2		1,2 3,4	1,2	2		1,2	1,2,3 5,6,7

D1-5	Drake Passage SR1b	I6	I6S (US partner)	(blue)	High-resolution models: model development, runs, adjoint	AB	Advisory Board meeting
S1-5	Scotia/Weddell A23	A2	ANDREX II	(purple)	Climate model analysis: CMIP5/6, ESM throughout	WS	Joint workshop with UKESM
24S	24 South	(hatched)	Gliders/ ASV	(green)	Observation-based analyses	IS	Intl. science mtg. (inc. AB)

Table 1: Structure of the ORCHESTRA programme, including phasing of observations, analyses and production of deliverables.

Risk will be managed in line with established NERC and institute methodologies, with the major initial elements to be considered being (1) rescheduling/curtailment of fieldwork; (2) underperformance/loss of autonomous vehicles; (3) loss/damage to moorings; (4) critical model code development by third parties. Initial mitigation strategies will be (1) fieldwork planned in climatically benign seasons, with the programme longevity enabling delays to be absorbed scientifically; (2) data from AUVs/ASV to be monitored in real-time to detect malfunctions, and environmental hazards tracked with EO data; (3) moorings to be deployed in full consultation with the NERC Moorings Advisory Group; (4) in-house software version control to be used to ensure that stable versions of code are quickly retrievable. The PI and Centre Leads all have strong track records in delivering complex, multi-stranded research programmes that include these types and levels of risk. Collectively they will ensure the production of deliverables on the timescale specified, with any major changes agreed with the PAG, Centre Directors and NERC before enactment.

8. Scalability: To accommodate a 20% reduction in the ORCHESTRA budget, the main elements that we would cut are high-resolution model development (T8), autonomous vehicle deployments (T3) and novel profiling float analyses (T2). Losing these elements would mean:-

- a restriction to evaluating existing models, rather than seeking to develop and test new schemes that will be integral to the next generation of models.
- focussing on proven observational platforms (ships and moorings) without extending their capability using autonomous platforms.

These cuts will permit ORCHESTRA to deliver a coherent programme but would:-

- compromise the ambition of ORCHESTRA to inform the next generation of UK climate/Earth System models with specific improvements in the Southern Ocean.
- fail to capitalise on the UK's capability, investment and experience in marine robotics, with consequent slowing of national progress in this high-profile area.
- remove the autonomous wintertime observations from the scientific analysis, thereby perpetuating the summer-season bias in observing.

A 20% increase in resource would enable us to create a new network for atmospheric observations, by establishing time series stations on key South Atlantic islands (St. Helena, Tristan, South Georgia, Signy). Weekly air samples would be collected for analysis of component gases (CO_2, CH_4, N_2O, O_2), with analysis carried out in collaboration with the University of East Anglia, who have complementary interests (see Project Partner statement; no funding dependency exists). Leverage will be obtained through existing CO_2 measurement programmes in the region (Ascension, Cape Point, Falkland Islands, Halley, Palmer, Syowa). Analysis of the data in an inverse modelling framework will enable the most accurate assessment of air-sea carbon fluxes for any ocean basin achieved hitherto, both in terms of magnitude, and the details of regional and temporal variability. Paralleling the atmospheric inverse analyses, ocean inversions based on profiling float data will be undertaken, including SOCCOM floats equipped with biogeochemical sensors. We will develop a technique to match the strength, variability and uncertainty of the divergences and convergences of the atmospheric and oceanic inversions, and hence give better-constrained fluxes overall, as well as enabling a dynamical understanding of the ocean processes responsible for the time-varying patterns in carbon flux.

9. Timeliness and Wider Relevance: The timeliness of ORCHESTRA is demonstrated not only by the pressing policy-relevant topics that the science will address but also by the inadequate representation of the Southern Ocean in the current generation of forced and coupled models, including those used for IPCC climate projections. Work to improve their representation beyond CMIP6 needs to begin now, with emphasis on eliminating the severe Southern Ocean temperature biases, and on improving the representation of the formation and export of key water masses.

Societally, the benefits to be gained by improving climate prediction are difficult to overstate, with more effective adaptation and mitigation strategies becoming feasible, and industry, commerce and other sectors provided with a more robust planning framework. In economic terms, the capacity of the global ocean to absorb carbon was recently estimated to have an asset value of $4.3 trillion (*15*); the Southern Ocean currently accounts for around half of this absorption. However, large uncertainties in the stability of the sink translate to an economic uncertainty envelope of >$10 billion p.a.; reducing this has potentially significant financial benefits. Politically, our programme will help sustain UK leadership in climate science, important for underpinning Government-level climate change negotiations and important for UK geopolitical influence. We will feed high-level results to key Government departments through direct links (e.g. Shuckburgh as climate advisor to DECC), through the IPCC process, and through partnership with the Met Office.

ORCHESTRA will provide a solid platform for future NERC/UK strategic research programmes via SPAG, and for other linked projects. There is considerable potential to expand the scope of ORCHESTRA by drawing in HEI partners including, *inter alia*, groups with whom we collaborate to use transient tracer data to constrain ocean ventilation timescales. ORCHESTRA will also provide opportunities for other scientific communities by delivering fieldwork opportunities, observations and models that have the capability to enhance studies of Antarctic ice sheet stability and sea-level rise, ocean acidification, marine ecosystems and biodiversity, and palaeoclimate. We will work closely with existing funded programmes of relevance to ORCHESTRA, including the NERC-funded project “Controls over Ocean Mesopelagic Interior Carbon Storage (COMICS)”. The ORCHESTRA and COMICS teams include commonality in personnel, and we will exploit scientific synergies and joint fieldwork opportunities. ORCHESTRA science and deliverables will benefit greatly other LTS-M programmes, most notably UKESM.

Internationally, ORCHESTRA will raise the profile of excellent UK research into the ocean’s role in climate. It will benefit (and leverage resource in-kind from) several international initiatives including SOCCOM, Argo, SAMOC (the South Atlantic Meridional Overturning Circulation consortium), GO-SHIP, and the Year of Polar Prediction. It will interface with international climate database programmes including the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and SOCAT, thus ensuring the widest uptake of NERC-funded data and science.

10. ORCHESTRA Legacy

Beyond the five-year time scale of ORCHESTRA, the cross-centre teams and *modus operandi* created in ORCHESTRA will persist, enabling future large strategic issues of a similar scale to be addressed. ORCHESTRA will deliver unique datasets on oceanography and biogeochemistry in the data-sparse Southern Ocean that will have value in perpetuity. These will be archived and made available via BODC (see Outline Data Management Plan). ORCHESTRA will leave a legacy of improved scientific capability in key disciplines that will endure and be deployable for future important issues. These include the development of new systems to measure fluxes of critical climatic properties, new model schemes for improved oceanographic and climate prediction, new techniques for processing data from autonomous instruments, and (in the +20% scenario) a new network for sustained measurement of atmospheric gases at island stations.

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Ocean Regulation of Climate by Heat and Carbon Sequestration and Transports (ORCHESTRA): Previous Track Record

The ORCHESTRA LTS-M programme represents an ambitious coordinated deployment of NERC National Capability (NC) funding to address one of the most important and pressing environmental issues facing us: the role of the ocean in dictating present and future climatic change. The scale and complexity of this issue is such that a collective approach involving each of the relevant NC-supported institutes is required, along with the creation of effective national and international linkages to relevant institutes and programmes around the world. The ORCHESTRA grouping has strong track records in each of the elements required, including ambitious fieldwork programmes to measure and understand the pattern and variability of ocean circulation [e.g. 1, 2], advanced ocean and climate modelling studies [3, 4], the development and implementation of innovative Earth Observation techniques [5, 6], and the design and use of novel platforms and sensors [7, 8]. The ORCHESTRA partners have demonstrable expertise in delivering world-class strategic results from these programmes, in order to tackle a range of the most pressing scientific questions.

The British Antarctic Survey (BAS) undertakes fundamental research in both polar regions and provides the UK's national capability for Antarctic science. The excellence of BAS science was rated very highly in the 2013 NERC Research Centre Evaluation (RCE2013), with 74% of research outputs being judged 3-4*. The team that rated highest within BAS was Polar Oceans, which will deliver the core of the BAS effort for ORCHESTRA. This team is led by Prof. Mike **Meredith,** BAS Deputy Director of Science and an Individual Merit Promotion (IMP3) scientist. He has published more than 100 papers in ISI-listed journals (current H-index of 37), and has led or co-led the delivery of several multi-institute programmes that have defined how we understand the structure and dynamics of the Southern Ocean [1, 9]. The Polar Oceans team is co-led Dr. Emily **Shuckburgh,** who specializes in the ocean's role in climate, and who excels at interactions with stakeholders and policymakers (currently an advisor to DECC). Within the Polar Oceans team, the Open Oceans group (led by Dr. Andrew **Meijers**) will contribute most significantly to ORCHESTRA. This team has an outstanding track record in delivering science of high quality and impact, including landmark assessments of the representation of the Southern Ocean in coupled models for the last IPCC assessment [10], paradigm-defining observations of the response of the Southern Ocean in large-scale climate change [6, 9], innovative use of autonomous instruments to quantify water mass structural changes in the Southern Ocean [11], and the use of geochemical tracers for determining the timescales and patterns of ocean circulation and their changes [12]. The group also has a strong track record in delivering key results pertaining to ocean mixing and circulation, via the use of ship-based techniques, moorings and autonomous ocean vehicles (Drs. Alex **Brearley,** Hugh **Venables,** Povl **Abrahamsen;** [13]). In addition, they have expertise with modeling high-latitude ocean circulation, and are leading wider UK efforts in building adjoint ocean models with an emphasis on understanding the climatic role of the Southern Ocean (Drs. Dan **Jones**, David **Munday;** [14, 15]). The BAS contribution to ORCHESTRA will be enhanced by the inclusion of the airborne meteorology group, and specifically the participation of Drs. Alexandra **Weiss** and Tom **Lachlan-Cope.** Lachlan-Cope led the development of the BAS meteorological research aircraft (MASIN) instrumentation, and continues to play a leading role in the use of this platform for atmospheric science in both polar regions. Weiss has conducted numerous MASIN campaigns, including as leader, with a track record in studies of air-sea-ice exchange processes, including the turbulent exchange of carbon dioxide [16, 17].

The National Oceanography Centre (NOC) is the focus for delivery of NC-funded marine science in the UK, and has the role of operating and delivering large-scale marine infrastructure and underpinning facilities for the UK community. It rated very highly in RCE2013, with 66% of research and 76% of impact studies being rated 3-4*. The NOC Marine Physics and Ocean Climate (MPOC) research group, which will contribute strongly to the delivery of ORCHESTRA, has an outstanding track record in devising, leading and conducting major observational programs, such as highly-successful Atlantic Meridional Overturning Circulation monitoring array (RAPID-AMOC [2]). NOC uses this expertise to contribute to the governance of the Global Ocean Observing System, though the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP; Elaine **McDonagh,** NOC lead for ORCHESTRA, is part of the Executive Group), Argo

(Dr Brian **King** is a member of the Steering Team), and the Joint WMO/IOC Commission for Oceanography and Marine Meteorology (JCOMM). This programmatic expertise underpins high-impact research quantifying ocean circulation, water mass variability, and the ocean's role in the climate system [18]. The NOC Marine Systems Modelling (MSM) group, headed by Prof. Adrian **New,** is the lead UK centre and a major contributor in the development, improvement and international oversight of the NEMO model (Nucleus for European Modelling of the Ocean), the main model scheme to be used by ORCHESTRA. This is developed jointly by MSM and the Met Office, which will ensure that model improvements developed in ORCHESTRA will be pulled-through fully by the Met Office. NOC modelling experts who will deliver these components of ORCHESTRA include Dr George **Nurser** [3, 4] and Dr. Joel **Hirschi** [2]. Collectively, and of strong relevance to ORCHESTRA, this group is leading the UK contribution to the Ocean Model Intercomparison Project (OMIP) component of CMIP6 for the upcoming IPCC assessment report. Further NOC research excellence that will be deployed to ORCHESTRA includes the assessment of air-sea fluxes and their impact on the ocean, via the participation of Dr Elizabeth **Kent** (Head of Surface Processes)**,** Dr Margaret **Yelland**, Prof. Simon **Josey** and other experts in marine meteorology [19, 20]. This group has extensive experience of delivering world-leading science and products, including landmark climatologies, innovative systems for flux measurements, and key assessments of surface exchanges, their uncertainties, and their impacts on ocean circulation and climate. In addition to physical observations, ORCHESTRA requires marine carbon and biogeochemical measurements, for which the NOC Ocean Biogeochemistry and Ecosystems (OBE) group has a strong track record including at-sea biogeochemical measurements and their interpretation on full-depth, basin-wide (GO-SHIP) sections and from Autonomous Surface Vehicles (Dr Sinhué **Torres-Valdés,** Susan **Hartman**). NOC experience in delivering large observational programs, development of state-of-the-art models, research to create new understanding of the oceans and their role in the earth system, and knowledge exchange for policy impact through the IPCC process will all be key to the success of ORCHESTRA.

The Plymouth Marine Laboratory (PML) is a NERC Collaborative Research Centre with a strong track record in conducting scientific research to address UK and international societal needs. Citation metrics place PML 8th in the world and 2nd in the UK for Oceanography (Thomson Reuters). PML has wide ranging capabilities in observing, modelling and understanding the marine environment in the open-ocean, estuarine, coastal and shelf waters, and has conducted extensive work on air/sea gas transfer for over 20 years, including the pioneering use of purposefully-released gas tracers in ocean circulation and mixing experiments. The PML contribution to ORCHESTRA will be led by Dr. Tim **Smyth,** who serves as Head of Science for Marine Biogeochemistry and Observations. He has a strong track record in delivering sustained observational programmes for NERC using NC funding, including the Western Channel Observatory and the Atlantic Meridional Transect [21]. He has >70 ISI publications (H=25) across a wide range of topics relevant to ORCHESTRA, including radiative transfer modelling, remote sensing and observational oceanography. Key to the delivery of ORCHESTRA is a greater understanding of air-sea exchange processes of heat, momentum and trace-gases, particularly using eddy-covariance techniques. PML participants involved in this include Dr. Tom **Bell*,*** a marine and atmospheric biogeochemist who recently spearheaded the International Surface Ocean-Lower Atmosphere Study (SOLAS) efforts to produce a range of global flux products. He developed the use of eddy covariance flux measurements whilst at the University of California, and has extensive sea-going and laboratory experience as well as a deep theoretical understanding of eddy covariance techniques [22]. Prof. Philip **Nightingale** leads the PML air/sea exchange team, and is an experienced authority on air/sea gas transfer. His use of deliberate tracers to obtain air/sea gas transfer rates is a seminal piece of work, with >550 citations [23]. He has >75 ISI publications (H=24) and has participated in over 30 field experiments including as chief scientist. PML will contribute further expertise to ORCHESTRA via Dr. Ming-Xi **Yang**, a marine and atmospheric biogeochemist with experience in making eddy covariance flux measurements in the open ocean and evaluating the role of surfactants in gas exchange and improving gas exchange models [24], and Dr. Vassilis **Kitidis**, a marine biogeochemist with research interests in surface ocean carbonate chemistry and CO_2 observations, net community production and photochemistry [25]. Kitidis is responsible for underway pCO_2 observations on-board NERC research vessels, including the RRS *James Clark Ross,* which are important for mapping the exchange of CO_2

between the surface ocean and the atmosphere in ORCHESTRA. Malcolm S. **Woodward** has been a Chemical Oceanographer at PML for 36 years, and is the Head of the Nutrient Facility. He has participated in >60 research cruises and is the Co-Chair of an International SCOR project: 'Towards Comparability of Global Nutrient Data'. This strong and relevant track record will ensure that the accurate and intensive measurement of nutrients required in ORCHESTRA to determine the flux of materials between the interior and upper ocean will be delivered.

The British Geological Survey (BGS) manages the NERC Earth Sciences Services & Facilities national capability, and hosts the NERC Isotope Geosciences Facilities (NIGF). The Stable Isotope Facility (SIF) is one node of the NIGF at the BGS. SIF has a strong track record in the measurements and provision of isotope data, with eight stable isotope ratio mass spectrometers in addition to chemical and sample preparation facilities and a small team of highly-trained technical and scientific staff. SIF has several world-leading capabilities including using the isotopes of oxygen and carbon (and other major elements) in a range of matrices including marine waters. Of particular relevance to ORCHESTRA, SIF has great expertise in high precision water oxygen and carbon isotope analysis for tracing inputs to ocean circulation and in ice core research, often conducted in conjunction with British Antarctic Survey [26, 27]. Prof Melanie **Leng** is the SIF Science Director and at the BGS the Director of the Centre for Environmental Geochemistry. She is also a Professor of Isotope Geosciences at the University of Nottingham. Leng leads environmental research within the SIF. She specialises in environmental studies including hydrology, modern process tracing, and palaeoceanography. She has co-authored more than 300 articles, has a Web of Science H-index of 37, and has been cited more than 5000 times.

The Centre for Polar Observation and Modelling (CPOM) has long-standing expertise in satellite observations and numerical models of the polar regions, combining these with theoretical understanding to form new and improved models of the Earth's ice, oceans and atmosphere. CPOM's role in ORCHESTRA will focus on providing satellite observations of sea ice freeboard and sea surface height between sea ice floes. This will exploit CPOM's 14 years of experience in the use of synthetic aperture radar (SAR) data to study ice motion, and 19 years of experience in the use of altimeter data to study ice elevation changes. Prof. Andrew **Shepherd**, Director of CPOM at the University of Leeds, will lead CPOM's contribution to ORCHESTRA. He has great expertise in satellite remote sensing of the cryosphere, with emphasis on the quantitative techniques of radar interferometry and radar altimetry [5, 28], and is Principal Scientific Advisor to the ESA CryoSat-2 mission. CPOM's contribution will be underpinned by technical expertise in satellite altimetry and SAR. Alan **Muir (**CPOM Systems Manager and Senior Software Engineer at University College London) specialises in space science software, systems and data management, and satellite radar altimetry of the cryosphere. Andrew **Ridout** (CPOM Scientist, UCL) provides technical support on satellite altimetry to polar oceanographic, sea ice and ice sheet research as well as to the CryoSat-2 mission. His current work concentrates on improving CPOM's retrievals of sea ice thickness through cross-calibrating the results with other missions, and validating the results with data from the Cryovex and IceBridge field campaigns. Importantly, he generated the first Cryosat-2 Arctic sea ice thickness map (2011) and the first map of seasonal variations in sea ice thickness (2012), and played a key role in the development of CPOM's recently launched near-real time sea ice data portal. Emma **Hatton** (CPOM SAR Facility Manager, Leeds) maintains and develops CPOM's SAR data processing systems. She has developed an end-to-end processing system for tracking ice motion using SAR data, and will apply this expertise to determine sea ice drift in the Southern Ocean. The CPOM activity will also be supported by the CPOM Directorate (Debbie **Rosen**, General Manager; Jenny **Dunhill**, Research Administrator), who will assist with development of Earth Observation data sets, managing work programmes, monitoring progress, and facilitating collaborations and knowledge exchange.

The Sea Mammal Research Unit (SMRU) is a NERC delivery partner embedded within the School of Biology at the University of St Andrews, and has pioneered the use of sophisticated data logging telemetry devices that have revolutionized research on the foraging distribution and behaviour of marine mammals and other large marine predators, while simultaneously collecting in situ ocean observations. SMRU received the Queen's Anniversary Prize in 2011 for promoting best practice in the health and governance of the ocean environment and developing practical solutions to track and conserve sea mammal populations and ecosystems. The impact of SMRU science was rated highly during the 2014 Research Excellence Framework (REF), for which SMRU delivered 4 out of 6 impact case studies of the School of Biology with 90% of all being judged 4* (2nd in the UK). Dr. Lars **Boehme** is a physical oceanographer at SMRU, whose research foci include the ocean overturning circulation, the dynamics of frontal systems, and the sensitivity of top predators to global and regional-scale climate variability [8, 29]. His research has led to a more strategic view of how to combine a range of observational approaches to achieve a cost-effective observation system linking physical observations to the range of trophic levels they drive. Clear examples of this work are the successful and widely-publicized SEaOS, SAVEX, MEOP and related projects that were built on technological developments of the SMRU instrumentation group, with the instruments used simultaneously gathering behavioural and physiological information about the animals as well as the environments they inhabit. Boehme also works closely with the British Oceanographic Data Centre on real-time data distribution, and is part of the MEOP consortium that recently made the quality controlled oceanographic data from animal-borne sensors available through a global portal.

Successful delivery of ORCHESTRA will require the scientific efforts of this diverse grouping of scientists to be coordinated and led effectively over its 5-year lifetime. This role will be assumed by **Meredith**, who has a strong track record of leading such national and international strategic endeavours, as evidenced by his instigation and leadership of the highly-successful Polar Oceans research programme at BAS, by his role as the inaugural Chair of the Southern Ocean Observing System, and by his role on the International Advisory Board of the Alfred Wegener Institute (Germany), as well as diverse other international activities. A project board will be established that contains the lead personnel from the participating organisations, each of whom has strong track records in the strategic management and leadership necessary to deliver the diverse elements of the research programme. These participants will be **McDonagh**, **Leng**, **Shepherd, New, Shuckburgh, Meijers, Kent** and **Boehme,** with a co-opted member being Dr. Helene **Hewitt** (Met Office; Manager of the Ocean Modelling Group). This group has the national and international standing and connections to ensure successful links are put in place, so as to maximise the scientific opportunities presented, and the uptake of the results generated. Examples of these connections and roles include membership of the NERC Strategic Programme Advisory Group (SPAG; Shuckburgh), Co-Chair of the JWCRP Joint Ocean Modelling Programme (Hewitt), membership of the International Connections Committee for the US SOCCOM project (Meredith), and numerous others, and will ensure that ORCHESTRA science is optimally developed and that uptake of ORCHESTRA science by key stakeholders is maximised.

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